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Study of Jet Recognition and Production Rates in Central $Pb - Pb$ Collisions with CMS

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Abstract

The possibility of jet recognition in central $Pb - Pb$ collisions with the CMS detector is studied. It is shown that for jets with transverse energies $E_T \geq 50$ GeV, the recognition efficiency is close to 100% with the background from “thermal” particles $12 \pm 3\%$. Expected statistics for $Pb - Pb$ interactions should be sufficient to study high E_T jet production for different values of the jet transverse energy and centrality of the collision.

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1 Introduction

The main motivation for heavy ion experiments at LHC is the observation and study of the phase transition from hadronic matter to the plasma of deconfined quarks and gluons (QGP). For heavy nuclei $A \sim 200$ colliding at the center of mass energies of about 5.5 TeV per nucleon pair, the energy density in central nucleus-nucleus collisions should be well above the expected phase transition value, thus allowing one to probe QGP in the asymptotically free ideal gas form [1, 2].

Several measurable effects have been considered to establish the existence of a phase transition in high energy heavy ion collisions. Among the proposed probes, high transverse momentum partons (jets) are especially promising, because they are produced at the early stage of the collision process, interact strongly with the constituents of the medium and escape before the final state hadronic interactions and decays take place. Multiple scattering of high P_T partons on dense matter constituents should lead to an enhanced acoplanarity and transverse momentum disbalance in two jet events [3, 4, 5, 6]. The medium-induced radiative energy loss of hard partons can also provide important information on jet quenching and modifications of the fragmentation function and jet profile [7, 8, 9]. Since multiple scattering and radiative energy loss of the hard parton have a rather weak dependence on the initial parton energy, it is desirable to keep the energy of jets as low as possible. However, for central heavy ion collisions, it is difficult to extract low transverse energy jets due to the large energy flow from the huge number of non-jet particles.

In the following, we present the results of our study of jet recognition and production rates for different transverse energy jets in central $Pb - Pb$ collisions at LHC with the CMS detector.

2 High E_T jet production in central $Pb - Pb$ collisions

At LHC ions will be accelerated up to the energies $E = E_p \times (2Z/A)$ per nucleon pair, where $E_p = 7$ TeV is the proton beam energy for LHC. In the case of Pb nuclei the energy per nucleon pair will be 5.5 TeV and the expected average luminosity for a single experiment is $L \approx 1.0 \times 10^{27}$ cm^{-2}s^{-1}. The interaction cross-section for $Pb - Pb$ collisions is about 7.5 b, which leads to an event rate of 7.5 kHz. In the present note, only central $Pb - Pb$ collisions with reduced impact parameter $b_r = b/b_{max} < 0.3$ are considered. The fraction of such events is about 10%.

The production cross section of high transverse momentum jets in minimum bias nucleus-nucleus collisions is extrapolated from that in *pp* interactions at the same energy ($\sqrt{s} = 5.5$ TeV), using the parametrization $\sigma_{AA} = A^{2\alpha} \times \sigma_{pp}$, with $\alpha = 1.0$. The cross-section for QCD jet production in *pp* collisions is evaluated using the PYTHIA Monte-Carlo program [10], with default structure functions CTEQ2L and a K-factor equal to 1. This approach does not take into account the effects of the deflection of the parton structure functions in a nucleus relative to a free nucleon, energy losses of hard partons and the modification of the jet profile in dense media.

To estimate the influence of the large number of secondary particles on jet recognition in central $Pb-Pb$ collisions, the high transverse momentum QCD jet events are superimposed on the “thermal” background. The important parameters for this study are: the multiplicity of “thermal” particles (mainly pions and kaons) and their transverse momentum distribution (especially the high P_T tail of the spectra). For the number of charged particles emitted per unit of rapidity in a central $Pb - Pb$ collision with $b_r = 0$, we assume $(dN_{ch}/dy)_{y=0} = 8000$, which is the upper limit of most theoretical expectations. Ratios of $N_{\pi^0}/N_{\pi^\pm} = 0.5$ and $N_{K^\pm}/N_{\pi^\pm} = 0.2$ are used independently of the impact parameter. The pseudorapidity distributions of π and K mesons are obtained according to the HIJING event generator [11]. The η spectra of these particles can be described by the sum of two Gaussian functions.

The transverse momentum distributions of particles in heavy ion collisions from the HIJING Monte Carlo is softer than in *pp* interactions due to the jet quenching effect. We however take harder spectra to be conservative in our estimations. For the P_T distribution of pions the following parameterization is used [12, 13]:

$$dN_\pi/dP_T{}^2 = A \times \exp(-\sqrt{M_\pi{}^2 + P_T{}^2}/T) \quad \text{for} \quad P_T < P_T{}^{lim} \tag{1}$$

$$B/(1 + P_T/P_T{}^0)^n \quad \text{for} \quad P_T > P_T{}^{lim} \tag{2}$$

where $B = A \times \exp(-\sqrt{M_\pi{}^2 + (P_T{}^{lim})^2}/T) \times (1 + P_T{}^{lim}/P_T{}^0)^n$.

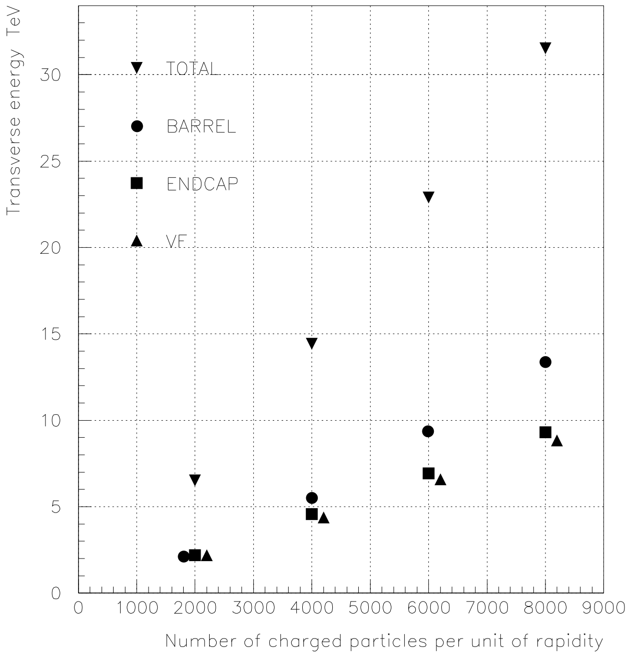

Figure 1: Dependence of the measured transverse energy on the multiplicity of charged particles.

The transverse momentum spectra of K mesons are obtained from the pion distribution:

$$dN_K/dP_T{}^2 = ((\sqrt{M_\pi{}^2 + P_T{}^2} + 2)/(\sqrt{M_K{}^2 + P_T{}^2} + 2))^m \times dN_\pi/dP_T{}^2 \quad (3)$$

The values of the parameters are: $T = 0.16$ GeV, $P_T{}^0 = 0.74$ GeV/c, $P_T{}^{lim} = 0.5$ GeV/c, $n = 7.2$ and $m = 12.3$, extracted from a fit of pion and kaon transverse momentum distributions in pp interactions from PYTHIA.

Detector response is modeled using the CMSJET program [14] in the pseudorapidity range $|\eta| \leq 5.0$. Figure 1 presents the dependence of the measured transverse energy on the number of secondary charged particles emitted per unit of rapidity in the central region in $Pb-Pb$ collisions for barrel, endcap and very forward parts of the CMS calorimetry. The thresholds on cell energies for electromagnetic, hadron and very forward calorimeters are 0.1, 0.5 and 1.0 GeV respectively. Measured transverse energy increases strongly with particle multiplicity, thus allowing to measure the centrality of the collision and select central $Pb-Pb$ interaction events with the E_T trigger. The ratio of measured to generated transverse energy also increases with multiplicity. A major fraction of the transverse energy is measured in barrel calorimeters due to the large number of particles emitted in the mid-rapidity range.

The jet recognition efficiency and expected production rates are studied at present only for the barrel calorimeters. The modified UA1-type jet finding algorithm is used in $\eta - \phi$ space. After finding a preliminary set of clusters, the merging/splitting procedure is applied for overlapping ones. Two clusters are merged into one jet if more than 75% of the transverse energy of the cluster with smaller E_T is contained in the overlap region. The direction and the energy of the new jet is then recalculated. If less than 75% of the E_T is contained in the overlap region, the clusters are split into two separate jets. The jet finding procedure is applied at three different stages of the simulation: i) at parton level; ii) at the particle level with all final state particles except neutrinos are taken into account without momentum smearing; iii) at the calorimeter level for the same QCD jet event superimposed on the “thermal” particle background. Results from the first two steps are used for the estimation of jet characteristics at the generator level and for the optimisation of the jet finding algorithm for heavy ion collision simulation (the third step). In order to reduce the contribution from “false” jets originating from fluctuations in the large transverse energy flow from non-jet particles, in central $Pb-Pb$ collisions it is necessary to use a narrow cone radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ in the jet finding algorithm [15, 16]. In our analysis, the value of $R = 0.3$ is used for cluster selection. It should be mentioned that in pp interactions about 80% of the jet transverse energy for high E_T jets (≈ 100 GeV) is contained within this radius [17, 18].

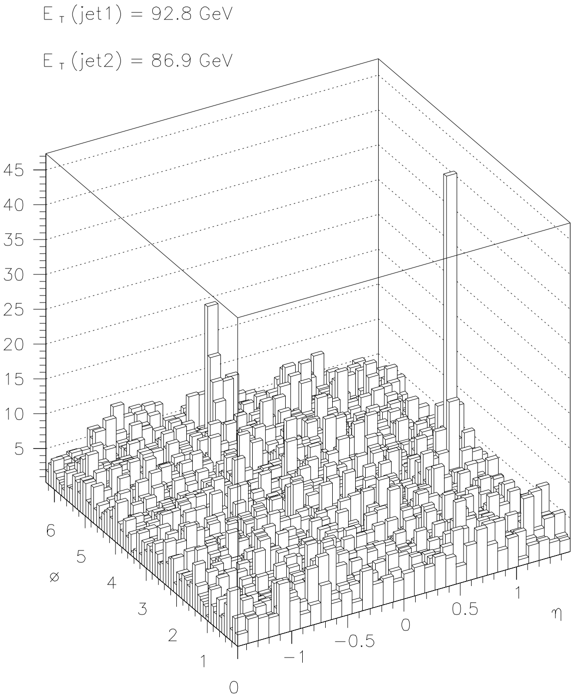

Figure 2: Transverse energy deposition in electromagnetic and hadron calorimeter cells for high E_T dijet event.

For heavy ion collisions, before applying the jet finding algorithm, a simple iterative procedure is used to determine the average transverse energy of electromagnetic and hadronic calorimeter cells. All cells with transverse energy greater than ${E_T}^{cell} > 3 \times \langle {E_T}^{cell} \rangle$ are excluded from the calculation of the average transverse energy, and the obtained value of $\langle {E_T}^{cell} \rangle$, multiplied by a factor κ, is subtracted from each cell. The value of κ is chosen to have a good matching between the generated and the reconstructed jet characteristics.

Figure 2 presents the transverse energy deposition in electromagnetic and hadronic calorimeter cells for two high E_T jets in the central $Pb - Pb$ collision. Although the fluctuations of the transverse energy flow are rather large, jets are still clearly visible over the background. The distributions of the difference in the transverse energy, pseudorapidity and azimuthal angle between the simulated and the reconstructed jets are shown in figure 3, for jets with $E_T \geq 100$ GeV. The precision in the reconstruction of the η and ϕ position of jets is slightly better than for the transverse energy ($\sigma(E_T)/E_T \approx 12\%$, $\sigma(\eta)/R \approx 10\%$ and $\sigma(\phi)/R \approx 6\%$).

Table 1 presents the ratios of reconstructed to simulated jet numbers, relative contribution of "false" jets, transverse energy resolution and expected production rates for two weeks of running time, for jets with different transverse energies. The ratio of reconstructed and simulated jet numbers is very close to 1, which means that high E_T jets are reconstructed with an efficiency of about 100%. The small difference between the numbers of simulated and reconstructed jets for $E_T \geq 50$ GeV is related to the determination of jet energy in calorimeters, and may be reduced by tuning the parameters of the jet finding algorithm. The contributions from "false" jets is $12 \pm 3\%$ for $E_T \geq 50$ GeV and becomes negligible for higher transverse energies. The resolution in jet transverse energy improves from 16.7% for $E_T \geq 50$ GeV to 8.6% for $E_T \geq 200$ GeV. For jet transverse energies lower than 50 GeV, the background contribution increases rapidly and the energy resolution is worse. The production rates are calculated for two weeks of running time at the average luminosity. If this luminosity has to be shared between two experiments, the luminosity for each experiment will be about one fourth of the design one. It should be mentioned that this estimation does not take into account the trigger efficiency and data acquisition system capabilities, which will reduce the event rate by a factor of few depending on the trigger specifications in real running. Even in this case the expected statistics will be enough to study high E_T jet production in $Pb - Pb$ interactions as a function of the impact parameter of the collision and the transverse energy of jets.

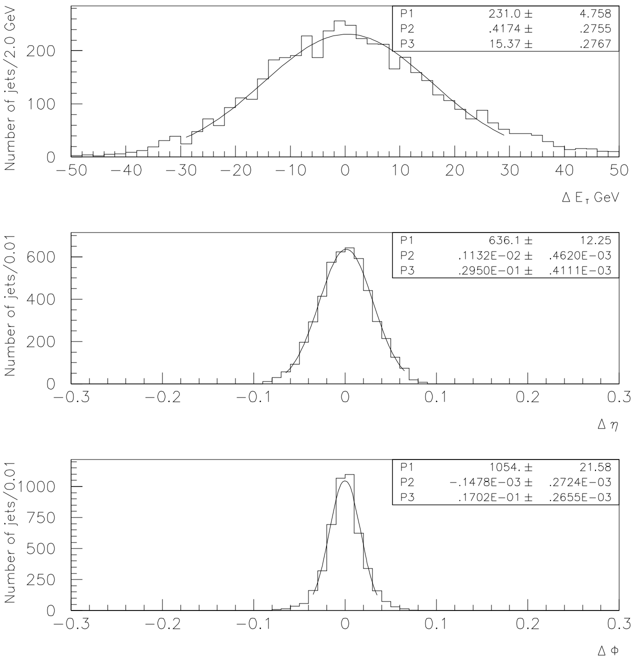

Figure 3: Distributions of differences in transverse energy, pseudorapidity and azimuthal angle between the simulated and reconstructed jets.

Table 1: Ratio of reconstructed to simulated jet numbers ϵ_1, contribution of "false" jets ϵ_2, transverse energy resolution and production rates, for jets with different transverse energies.

$E_T \geq$, GeV	ϵ_1	ϵ_2	$\sigma(E_T)/E_T, \%$	Rate
50	0.94 ± 0.03	0.120 ± 0.030	16.7	$1.7 \cdot 10^7$
100	1.03 ± 0.02	0.010 ± 0.004	11.6	$1.2 \cdot 10^6$
150	0.98 ± 0.02	0.004 ± 0.003	9.2	$2.1 \cdot 10^5$
200	0.99 ± 0.02	0.004 ± 0.003	8.6	$5.3 \cdot 10^4$

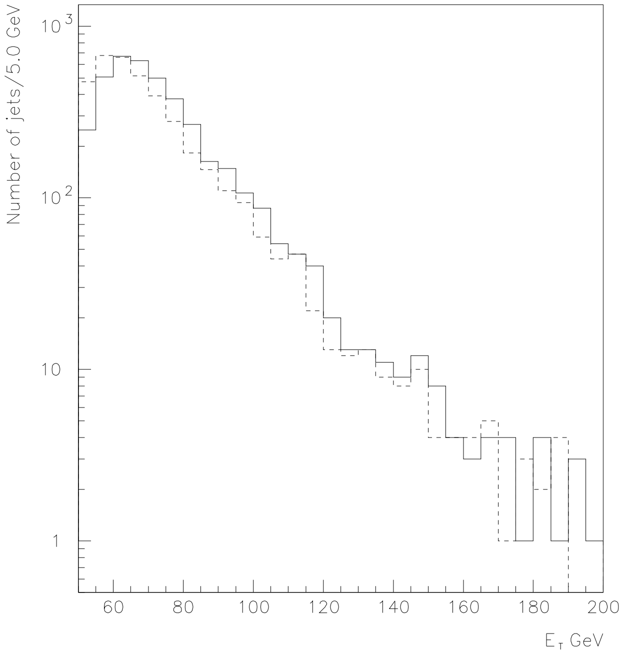

Figure 4: Distributions of transverse energy for jets: with $E_T \geq 50$ GeV (full line) same jets with reduced energy due to the propagation through the dense matter (dashed line).

3 Results and conclusion

We have performed a Monte Carlo study of jet recognition and production rates for high transverse energy jets in central $Pb-Pb$ collisions at LHC, with the CMS detector. The jet recognition efficiency for $E_T \geq 50$ GeV jets is found to be close to 100% with a background of $12 \pm 3\%$. The contribution of "false" jets can be further suppressed by requiring two jets to be approximately back-to-back in the transverse plane. For the jets with transverse energy lower than 50 GeV, the background contribution increases rapidly and the energy resolution becomes worse. This makes the use of low E_T jets questionable for the study of medium-induced effects. However, the estimated production rates for high transverse energy jets should be sufficient to study jet production in a wide range of E_T and for different centrality of the collision.

The accuracy in the determination of the jet transverse energy in high energy heavy ion collisions is limited due to the large transverse energy flow of non-jet particles and its fluctuations. We find $\sigma(E_T)/E_T = 16.7\%$ for jets with $E_T \geq 50$ GeV, improving to 8.6% for $E_T \geq 200$ GeV jets. Jet energy smearing because of resolution effects makes the study of jet quenching using only the E_T distribution rather difficult (see also [19]). As an illustration, figure 4 shows the measured transverse energy spectra for jets with $E_T \geq 50$ GeV, together with the "quenched" distribution obtained from the initial one under the assumption that jets propagating through the dense medium lose on average 5 GeV (distributed as a gaussian with $\sigma = 1$ GeV).

It is clear that significantly higher statistics is required to distinguish the two distributions. However, after two weeks of running, the CMS detector will be able to collect about 10^3 times more QCD jet events with $E_T \geq 50$ GeV, than the presented one. Thus, a 20% effect should be easily detectable. In addition, multiple scattering and medium-induced radiative energy loss of the hard parton should also lead to the potentially measurable modifications in the acoplanarity of dijet events and jet profiles. In order to simulate and study the possibility of such measurements, more explicit and precise theoretical calculations of multiple scattering and medium-induced radiative energy loss effects are necessary. Note also, that additional processes like $\gamma + jet$ and $Z(\rightarrow \mu^+\mu^-) + jet$ production in heavy ion collisions should also provide an insight on the influence of dense hadronic media and a possible phase transition on jet properties [20, 21].

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